

The metallicity of the long GRB hosts and the Fundamental Metallicity Relation of low-mass galaxies

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ABSTRACT

We investigate the metallicity properties of host galaxies of long Gamma-ray Bursts (GRBs) in the light of the Fundamental Metallicity Relation (FMR), the tight dependence of metallicity on mass and SFR recently discovered for SDSS galaxies with stellar masses above $10^{9.2}M_{\odot}$. As most of the GRB hosts have masses below this limit, the FMR can only be used after an extension towards lower masses. At this aim, we study the FMR for galaxies with masses down to $\sim 10^{8.3}M_{\odot}$, finding that the FMR does extend smoothly at lower masses, albeit with a much larger scatter. We then compare the resulting FMR with the metallicity properties of 18 host galaxies of long GRBs. While the GRB hosts show a systematic offset with respect to the mass-metallicity relation, they are fully consistent with the FMR. This shows that the difference with the mass-metallicity relation is due to higher than average SFRs, and that GRBs with optical afterglows do not preferentially select low-metallicity hosts among the star-forming galaxies. The apparent low metallicity is therefore a consequence of the occurrence of long GRB in low mass, actively star-forming galaxies, known to dominate the current cosmic SFR.

Key words: gamma ray: bursts - Galaxies: star formation - Galaxies: abundances

1 INTRODUCTION

Gamma-ray bursts (GRBs) are the most energetic explosions in the Universe (see Zhang & Mészáros 2004 for a review) and detected in the γ -rays with a frequency of about one per day over the whole sky. The γ -ray emission is accompanied by a long-lasting tail, called afterglow, usually detected over the whole electromagnetic spectrum. Their extreme brightness easily over-shine the luminosity of their host galaxy and makes them detectable up to extreme high redshift as shown by the discovery of GRB 090423 at $z = 8.2$ (Salvaterra et al. 2009; Tanvir et al. 2009). GRBs are usually divided in two, broad classes (Kouveliotou et al. 1993): short GRBs, which are believed to result from the merger of two compact objects, and long GRBs, associated to the collapse of the core of a massive star, as a Wolf Rayet star (Yoon et al. 2006; Woosley & Heger 2006; Yoon et al. 2008). In this paper, we limit our analysis to the class of long GRBs.

Recent studies on the final evolutionary stages of massive stars (Woosley & Heger 2006; Fryer et al. 1999) have suggested that a Wolf-Rayet star can produce a long GRB if its mass loss rate is small, which is possible only if the metallicity of the star is lower than $\sim 0.1 - 0.3 Z_{\odot}$. In this case,

the specific angular momentum of the progenitor allows the loss of the hydrogen envelope while preserving the helium core. In this view, GRBs may occur preferentially in galaxies with low-metallicity (Fynbo et al. 2003; Prochaska et al. 2004; Fruchter et al. 2006; Stanek et al. 2006), although we have to stress that low-metallicity progenitors do not necessarily imply low-metallicity host galaxies. Indeed, owing to the existence of metallicity gradients inside galaxies, GRBs could form from low-metallicity progenitors also in hosts with relatively high metallicities (Campisi et al. 2009).

Up to now, we have been able to detect the host galaxy of ~ 70 long GRBs with known redshift. In more than half of the cases, the observations allowed to determine the stellar mass and the star formation rate of the galaxy¹. The observational information gathered so far indicates that long GRBs with optical afterglows are typically found to reside in low-mass, dwarf galaxies with average stellar masses $M_{\star} \sim 1 - 5 \times 10^9 M_{\odot}$ and high specific star formation rate (SSFR=SFR/ M_{\star}). Information about the chemical content of this objects are known only for a subsample of the hosts (Savaglio et al. 2009; Levesque et al. 2010d,c). While most of the long GRBs are in low-metallicity galaxies, a few cases

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¹ Data taken from <http://www.grbhosts.org/>, see Savaglio et al. (2007)

for which the galaxy metallicity is found to be quite high do exist (e.g. GRB 020819, Levesque et al. 2010c; Küpcü Yoldaş et al. 2010, and GRB 050401, Watson et al. 2006), so that the role of metallicity in driving the GRB phenomena remains unclear and it is still debated (Fynbo et al. 2003; Prochaska et al. 2004; Stanek et al. 2006; Fynbo et al. 2006; Wolf & Podsiadlowski 2007; Price et al. 2007; Modjaz et al. 2008; Kocevski et al. 2009; Savaglio et al. 2009; Graham et al. 2009b,a; Levesque et al. 2010a,c,e; Svensson et al. 2010; Fan et al. 2010).

Many recent studies have attempted to find similarities and differences between the GRB host population and the normal field galaxy one (see, for example, Fynbo et al. 2008). In particular, these studies compared the observed mass-metallicity relation (or luminosity-metallicity relation) of the two populations obtaining contradictory results. From the analysis of a whole sample of known GRB hosts, Savaglio et al. (2009) concluded that there is no clear indication that GRB host galaxies belong to a special population. Their properties are those expected for normal star-forming galaxies, from the local to the most distant universe. On the other hand, the study of sub-samples with well-determined chemical properties (e.g. Levesque et al. 2010a,c; Han et al. 2010) suggests that most of the long GRB host galaxies fall below the $M - Z$ relation for the normal galaxy population.

The aim of this work is to further test the differences between GRB hosts and field galaxies by taking advantage of the new Fundamental Metallicity Relation (FMR) recently introduced by Mannucci et al. (2010). The FMR is a tight relation between stellar mass M_* , SFR and gas-phase metallicity. Local SDSS galaxies define a surface in the 3D space of these three quantities, with metallicity well determined by stellar mass and SFR. The residual metallicity scatter around this surface is very small, about 0.05 dex, similar to the expected uncertainties. Also, the same FMR defined locally by SDSS galaxies is found to describe, without any evolution, the properties of high-redshift galaxies, up to $z=2.5$. The origin of the strong, monotonic evolution of the mass-metallicity relation over the same redshift range (e.g., Tremonti et al. 2004; Erb et al. 2006b) is due to the increase of target SFR with redshift, resulting in sampling different parts of the same FMR at different redshifts. At even higher redshifts, galaxies are found to evolve off the FMR (Maiolino et al. 2008; Mannucci et al. 2009), and this effect is under test with a larger number of observations (Troncoso et al., in prep.).

The ranges of mass and SFR over which the FMR was measured are limited by the number of galaxies in the SDSS-DR7 sample used, which become rare at $\log(M_*/M_\odot)$ below 9.2 and above 11.4, and at $\log(\text{SFR}/M_\odot \text{ yr}^{-1})$ below -1.4 and above +0.8. For this reason, a comparison with the hosts of GRBs can only be done by extending this relation using lower mass galaxies, while a simple extrapolation of the FMR of massive galaxies could produce spurious effects.

2 EXTENDING THE FMR TOWARDS SMALLER MASSES

To derive the FMR, Mannucci et al. (2010) have split ~ 140000 SDSS-DR7 galaxies into bins of mass and SFR having width of 0.15dex in both quantities. To have a good estimate of both median and dispersion of the metallicity for each value of mass and SFR, only bins containing more than 50 galaxies have been used. This severely limits the range of mass and SFR over which the FMR has been measured, even if a significant number of galaxies outside these ranges are present in the original sample. Among the ~ 140000 SDSS-DR7 galaxies selected by Mannucci et al. (2010) requiring $0.07 < z < 0.30$ and signal-to-noise ratio $\text{SNR}(\text{H}\alpha) > 25$, about 2000 (1.4%) have masses below $10^{9.2} M_\odot$. Here we intend to use these galaxies to extend the measured FMR.

Mannucci et al. (2010) have introduced the new quantity μ_α defined as a linear combination of stellar mass and SFR:

$$\mu_\alpha = \log(M_*) - \alpha \log(\text{SFR}) \quad (1)$$

and have demonstrated that, for $\alpha=0.32$, all galaxies at $z < 2.5$ show the same dependence of metallicity on $\mu_{0.32}$ and the same range of values of $\mu_{0.32}$. In other words, the introduction of this quantity roughly defines a projection of the FMR that minimizes the scatter, i.e., corresponds to observing the FMR "edge on". From a physical point of view, metallicity is found to increase with mass and decrease with SFR, therefore a combination of these two quantities, with a negative factor for SFR, is expected, and found, to show a better correlation with metallicity. It is worth noticing that the dependence of metallicity only on $\mu_{0.32}$ is not exact, as no part of the FMR is exactly a plane (see Fig. 2 of Mannucci et al. 2010), nevertheless this is a convenient approximation.

To avoid binning the limited number of galaxies with low mass into a large number of classes of mass and SFR, we extend the FMR directly by considering the combination $\mu_{0.32}$. We consider the ~ 1400 galaxies in Mannucci et al. (2010) sample with $8.3 < \mu_{0.32} < 9.4$. This is a small sample, side by side to the large sample of ~ 140.000 galaxies with larger values of $\mu_{0.32}$, and problems with contamination are possible. Indeed, while ~ 1300 galaxies with low $\mu_{0.32}$ show low metallicities, 86 of them, corresponding to 0.0007 of the full sample, have large values of metallicities, above $12 + \log(\text{O}/\text{H}) = 8.9$, with the same distribution of metallicity of the large population of massive, quiescent, metal-rich galaxies. Given the intrinsic uncertainties on mass and SFR, these 86 galaxies are likely to be metal-rich galaxies whose $\mu_{0.32}$ is incorrectly measured and scattered towards low values. We remove these galaxies from the sample, and divide the remaining ~ 1300 galaxies in bins of $\mu_{0.32}$, and for each bin we compute median and standard deviation of metallicity. For comparison, we also compute the mass-metallicity relation considering the ~ 1700 galaxies with masses between $10^{8.3}$ and $10^{9.4} M_\odot$.

The results are shown in figure 1, where low-mass galaxies are compared to galaxies of larger M_* . The left panel shows the mass-metallicity relation. At masses above $\sim 10^{10} M_\odot$ this is fully consistent with Tremonti et al. (2004), while it shows lower values of metallicity and a steeper

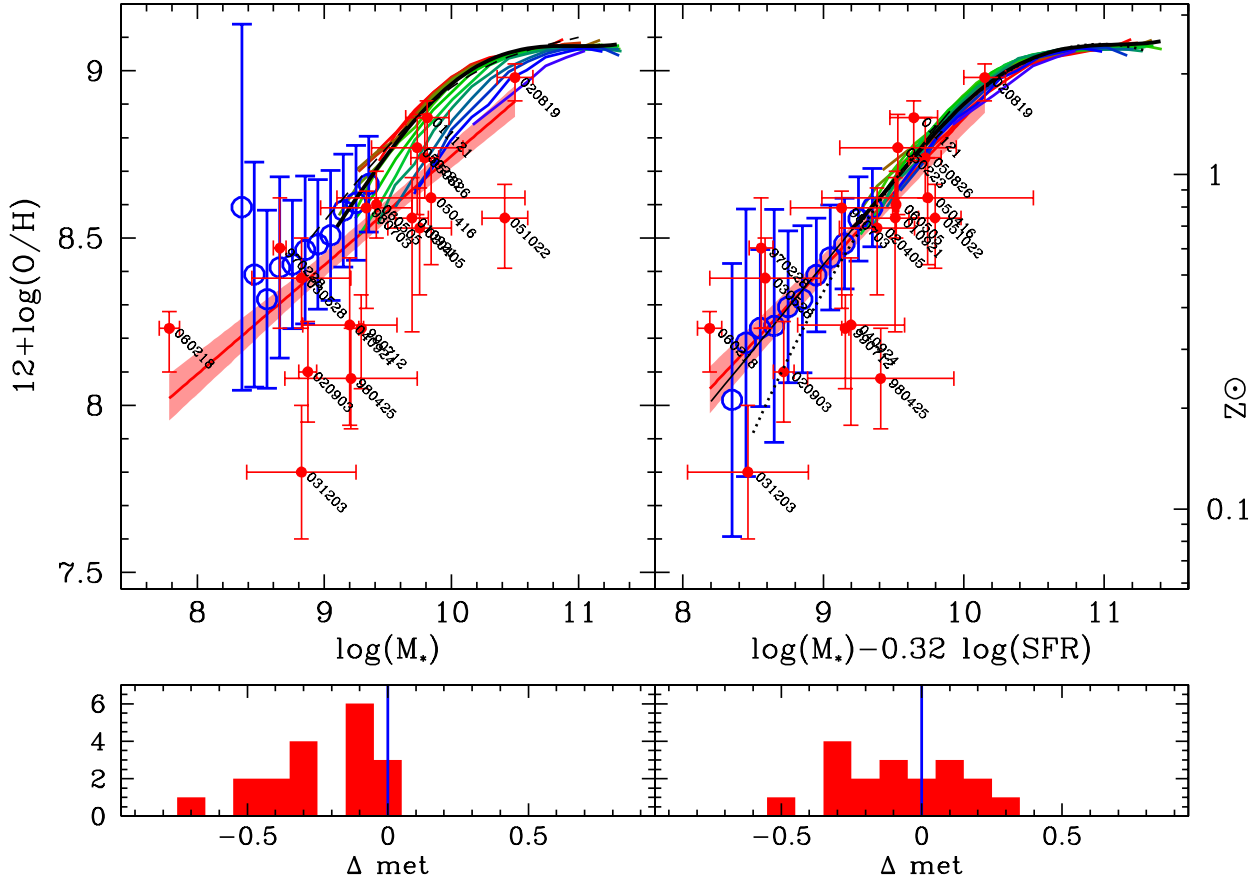


Figure 1. *Left:* Mass-Metallicity: metallicity of low-mass SDSS galaxies (blue open dots with 1σ dispersions) as a function of stellar mass. The coloured lines are local SDSS galaxies from Mannucci et al. (2010), color-coded from red to blue according to increasing SFR. The black thick line shows the polynomial fit to the mass-metallicity relation in Mannucci et al. (2010). The black dashed line is the mass-metallicity relation in Jabran Zahid et al. (2010), transformed to the same metallicity scale. The host galaxies of long GRBs are over-plotted (red solid dots, labelled with the GRB date). The red thick line is a linear fit to these GRB host data, with $\pm 1\sigma$ bands shown in light red. It is clear that GRB host follow a different relation and show systematically lower metallicities. The *lower panel* shows the difference between the metallicity of the GRB hosts and the mass-metallicity relation of SDSS galaxies, showing the systematic offset toward lower metallicities. *Right:* Fundamental metallicity relation: metallicity as a function of $\mu_{0.32} = \log(M_*) - 0.32 \log(\text{SFR})$ in solar units. The black solid line is the linear fit to the low-mass SDSS galaxies. For comparison, the black dotted line is the extrapolation of the 2nd degree fit to the FMR of the SDSS galaxies as defined in Mannucci et al. (2010) and plotted for $\text{SFR}=0$. The linear fit to the GRB host data (red line with the $\pm 1\sigma$ band) shows that GRB hosts are fully compatible with the FMR defined by local SDSS galaxies. This is also shown in the lower panel, where the metallicity difference of GRB hosts with the FMR is plotted.

slope at lower masses. This is probably due to the different selections: our requirement of a high signal-to-noise ratio ($\text{SNR} > 25$, see Mannucci et al. 2010) in the $\text{H}\alpha$ line preferentially select galaxies with high SFR and, as a consequence, lower metallicity, especially at low stellar masses.

On the right of figure 1, the FMR is shown. Low mass galaxies appear to extend smoothly the FMR, with a linear relation between metallicity and $\mu_{0.32}$. The resulting FMR can be described by:

$$\begin{aligned} 12 + \log(\text{O}/\text{H}) &= 8.90 + 0.37m - 0.14s - 0.19m^2 \\ &\quad + 0.12ms - 0.054s^2 \quad \text{for } \mu_{0.32} \geq 9.5 \quad (2) \\ &= 8.93 + 0.51(\mu_{0.32} - 10) \quad \text{for } \mu_{0.32} < 9.5 \end{aligned}$$

where $m = \log(M_*) - 10$ and $s = \log(\text{SFR})$ in solar units.

It is evident that the intrinsic scatter around the FMR increases towards lower values of $\mu_{0.32}$. The residual scatter

is larger than the expected errors on metallicity, mass and SFR, even if the uncertainties on stellar masses from SED fitting could increase towards low masses. This increasing scatter towards dwarf galaxies is a well known effect probably related to a large spread of histories and current levels of star formation (Hunter & Hoffman 1999; Hunt et al. 2005; Zhao et al. 2010).

3 THE METALLICITY OF THE HOSTS OF GRB

The formation of long GRBs is thought to be related to the collapse of a very massive, low metallicity star (Woosley & Heger 2006; Fryer et al. 1999). Thus, it has been argued that the occurrence of a long GRB may be linked to an overall low

metal content of its host galaxy, making GRB hosts a biased galaxy sample with respect to the normal field population. In order to check whether this bias exists, we consider the properties of the GRB hosts in the light of the observed FMR for normal field galaxies. To this extent, we collect all the GRB host galaxies at $z < 1$ with available observations to measure, at the same time, stellar mass, SFR, and gas phase metallicity.

Line fluxes of long GRB hosts have been published by several authors (Savaglio et al. 2009; Han et al. 2010; Levesque et al. 2010b). We have used these compilations to measure gas-phase metallicities, using the method described in Maiolino et al. (2008) and Cresci et al. (2010), and expressing it in the same scale as in Nagao et al. (2006), Kewley & Ellison (2008), and Mannucci et al. (2010), where solar metallicity is $12 + \log(\text{O}/\text{H}) = 8.69$. Many metallicity indicators have been proposed that are based on line ratios (e.g., Pettini & Pagel 2004; Nagao et al. 2006; Kewley & Ellison 2008), but none of them is without problem. For example, R23 has two branches, with two different metallicities associated to each value of R23. Both $\text{H}\alpha/[\text{NII}]\lambda 6584$ and $[\text{OII}]\lambda 3727/[\text{NeIII}]\lambda 3869$ have monotonic variations with metallicity and no dependence on extinction, but they include fainter lines, especially for very high or very-low metallicities. $[\text{OIII}]\lambda 4958, 5007/[\text{OII}]\lambda 3727$ and $[\text{OIII}]\lambda 4958, 5007/[\text{NII}]\lambda 6584$ are sensitive to extinction, which is usually poorly known. Following Nagao et al. (2006), we measure metallicities by simultaneously considering all the flux ratios among the relevant emission lines, fitting these values with two free parameters, metallicity and extinction. Usually this method can obtain a reliable value of metallicity, avoiding or mitigating the intrinsic problems of each individual line ratio. In contrast, extinction is usually very poorly constrained, because most of the line ratios used involve line with similar wavelengths. For this reason, when flux ratios between different hydrogen Balmer lines are available and give consistent results, we measure extinction from these Balmer decrement (assuming intrinsic line ratios of $\text{H}\alpha/\text{H}\beta = 2.87$, $\text{H}\gamma/\text{H}\beta = 0.466$, $\text{H}\delta/\text{H}\beta = 0.256$, Osterbrock 1989), considerably reducing the uncertainties on A_V . The SFR is then obtained, as in Mannucci et al. (2010), from $\text{H}\alpha$ corrected for extinction, using the calibration in Kennicutt (1998). Uncertainties on the SFR are computed taking into account the errors on both line fluxes and dust extinction. Finally stellar masses are taken from Savaglio et al. (2009). Table 1 lists the resulting properties of the host galaxies in terms of stellar mass, SFR, gas-phase metallicity, and intrinsic dust extinction.

These data are plotted in fig. 1 and compared with both the mass-metallicity relation (left panel) and the FMR (right panel) of local SDSS galaxies. We computed a linear fit to the GRB host data taking into account the errors on metallicity, mass and SFR. The comparison with the mass-metallicity relation shows that, as already obtained by Levesque et al. (2010b) and Han et al. (2010), GRB host galaxies have lower metallicity than galaxies of the same mass both in the local universe (SDSS galaxies) and at intermediate redshift (Savaglio et al. 2005; Jabran Zahid et al. 2010). In contrast, we also find that GRB hosts do follow the FMR and its extension towards low masses, without any significant discrepancy. In other words, when the dependence on SFR is properly taken into account, the metallicity prop-

Table 1. Properties of the GRB hosts

GRB	z	$\log(M_*)$ (M_\odot)	SFR (M_\odot/yr)	$12 + \log(\text{O}/\text{H})$	A_V
970228	0.695	8.65 ± 0.05	1.95 ± 0.22	$8.47^{+0.15}_{-0.24}$	$0.0^{+0.7}_{-0.0}$
980425	0.0085	9.21 ± 0.52	0.24 ± 0.05	$8.08^{+0.15}_{-0.15}$	$1.9^{+0.1}_{-0.1}$
980703	0.966	9.33 ± 0.36	4.20 ± 0.17	$8.59^{+0.05}_{-0.30}$	$0.0^{+0.7}_{-0.0}$
990712	0.434	9.29 ± 0.02	2.62 ± 0.05	$8.23^{+0.10}_{-0.18}$	$0.5^{+0.1}_{-0.1}$
010921	0.451	9.69 ± 0.13	3.60 ± 0.32	$8.56^{+0.12}_{-0.34}$	$1.6^{+1.0}_{-1.0}$
011121	0.362	9.81 ± 0.17	3.30 ± 0.05	$8.86^{+0.05}_{-0.13}$	$0.9^{+0.1}_{-0.1}$
020405	0.691	9.75 ± 0.25	14.1 ± 0.29	$8.53^{+0.12}_{-0.20}$	$1.9^{+0.6}_{-0.6}$
020819B	0.411	10.50 ± 0.14	12.5 ± 0.17	$8.98^{+0.07}_{-0.16}$	$1.8^{+0.5}_{-0.5}$
020903	0.251	8.87 ± 0.07	3.00 ± 0.08	$8.05^{+0.10}_{-0.15}$	$0.8^{+0.2}_{-0.2}$
030528	0.782	8.82 ± 0.39	5.40 ± 0.19	$8.38^{+0.12}_{-0.15}$	$0.0^{+0.8}_{-0.0}$
031203	0.1055	8.82 ± 0.43	13.1 ± 0.05	$7.80^{+0.20}_{-0.20}$	$0.0^{+0.2}_{-0.0}$
040924	0.858	9.20 ± 0.37	1.02 ± 0.58	$8.23^{+0.20}_{-0.30}$	$0.0^{+1.2}_{-0.0}$
050223	0.584	9.73 ± 0.36	4.20 ± 0.64	$8.77^{+0.10}_{-0.20}$	$1.5^{+1.4}_{-1.3}$
050416	0.6528	9.84 ± 0.74	2.00 ± 0.43	$8.62^{+0.12}_{-0.20}$	$0.7^{+1.1}_{-0.7}$
050826	0.296	9.79 ± 0.11	1.60 ± 0.10	$8.74^{+0.12}_{-0.12}$	$0.1^{+0.2}_{-0.1}$
051022	0.8070	10.42 ± 0.18	89.6 ± 0.15	$8.56^{+0.10}_{-0.15}$	$1.0^{+0.3}_{-0.3}$
060218	0.0334	7.78 ± 0.08	0.052 ± 0.10	$8.23^{+0.05}_{-0.13}$	$0.5^{+0.3}_{-0.3}$
060505	0.0889	9.41 ± 0.01	0.46 ± 0.05	$8.60^{+0.10}_{-0.10}$	$0.8^{+0.1}_{-0.1}$

erties of long GRB hosts do not differ substantially from those of the typical field population. As explained in the discussion, this means that the low metallicities are associated to both low masses and high SFR, i.e. to high SSFR.

We stress that such a good agreement is only obtained when the original FMR is extended using low-mass galaxies. The use of an extrapolation of the original 2nd-order fit would produce a spurious difference in metallicity, with GRB hosts more metal rich than field galaxies.

In figure 2 we plot the relation between SSFR and metallicity for the 18 GRB host galaxies of our sample compared to the local SDSS galaxies. Here the color code shows different values of stellar mass. The solid lines show the relation between mass and SSFR for field galaxies, and the shaded area accounts for the intrinsic scatter of the observed relation for SDSS galaxies. GRB hosts populate the plot similarly to normal field galaxy population, with more (less) massive hosts lying in the upper (lower) bound of the observed relation. As already discussed, host metallicities are in line with those expected for star forming, field objects, apart GRB 980425. Notably, all the GRB hosts are found to present relatively high SSFR, with $\log(\text{SSFR}) \geq -10$. Their growth time, i.e. the time required by the galaxy to form its observed stellar mass at the present level of SFR, i.e. $1/\text{SSFR}$, is shorter than the Hubble time at the redshift of the GRB, for all objects in our sample. This indicates that GRB host are forming quite efficiently their stars similarly to local starbursts.

4 DISCUSSION

We have compared the metallicity properties of a sample of 18 GRB host galaxies with those of the local field population. In particular, we have found that GRB hosts do follow the FMR recently found by Mannucci et al. (2010). This fact implies that GRB hosts do not differ substantially

of the metal enrichment history at these early cosmic epochs is of uttermost importance to better understand the first stages of galaxy formation in the Universe and to constrain the properties of those galaxies that have re-ionized the intergalactic medium (see Salvaterra et al. 2010).

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